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(54) Title: DOWNLINK CHANNEL ESTIMATION EMPLOYING NON-POLLUTING DUMMY PILOT CODES
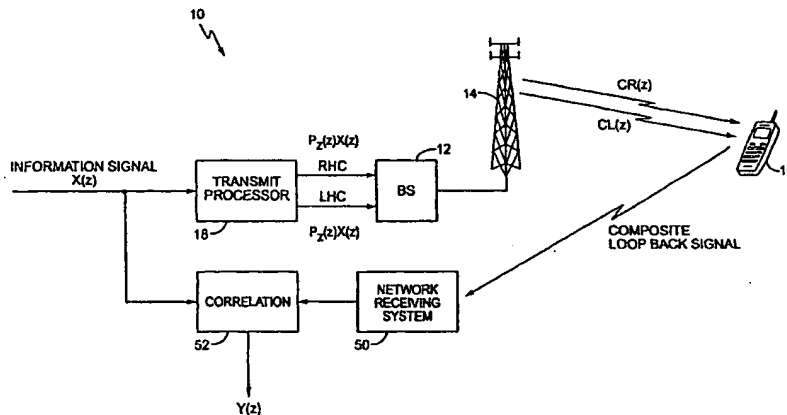
(57) Abstract: Transmitting non-polluting dummy pilot signals in a wireless communication network permits estimation of the downlink propagation channels between a number of joint transmitters and a lesser number of receivers. With fewer receivers than transmitters, loop back information from the receivers is not sufficient to determine the downlink propagation channels between the transmitters and receivers. For N transmitters and M receivers, (N-M) dummy pilot symbols are transmitted to facilitate downlink channel estimation. Each dummy pilot signal is transmitted to an imagined or dummy receiver that is virtually located such that its downlink channel coefficient vector is orthogonal to those of the real receivers. Transmit pre-filtering based on estimated propagation channels is applied to the information signals for the real receivers and to the dummy pilot signals. The extent to which the dummy pilot signals interfere at each receiver is an indication of mismatch between estimated and actual propagation channels.

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DOWNLINK CHANNEL ESTIMATION EMPLOYING NON-POLLUTING DUMMY PILOT CODES

BACKGROUND OF THE INVENTION

The present invention generally relates to wireless communication networks, and particularly relates to using non-polluting pilot codes in wireless networks employing
5   coherent transmit diversity techniques that improve communication performance and efficiency.

Wireless communication networks employ various techniques to maximize their communication efficiency, performance, and economy. Economy and efficiency may be measured from the service provider's perspective, and generally relate to supporting the
10   greatest possible number of users for lowest possible service and equipment costs. Performance may be measured from the perspective of both service providers and subscribers, and centers on providing the highest possible reliability at whatever data rate is being used.

Approaches to improving communication reliability are at least as numerous as
15   the factors influencing that reliability. Thus, one sees a broad range of technologies and methods in modern communication systems, all meant to improve the underlying reliability of the communication services provided. Of these varied approaches, diversity communications itself represents a varied mix of techniques.

In wireless communication, successful reception depends on a relatively
20   unobstructed signal path between a receiver and a supporting transmitter. If the path is obstructed, fading may occur. Fading may be particularly problematic when the wireless receiver is moving with respect to the transmitter. In this scenario, the signal path is ever changing and fading becomes a highly dynamic factor influencing reception quality.

Diversity combats fading by providing additional communication elements capable
25   of transmitting or receiving on different signal paths in the hope that at least one of these signal paths will remain un-faded at any particular instant in time. Diversity may be

implemented on the transmit side using different frequencies, antennas, polarizations, or combinations thereof to transmit to a given receiver.

Implementing diversity on the receive side, which is a more common practice, usually entails providing multiple receiving elements, such as two or more receive

5   antennas. With multiple receiving elements, the receiver may receive its signal of interest on multiple signal paths, thus increasing the likelihood that at least one of the signal paths will be unobstructed at any instant in time.

With transmit macro-diversity multiple transmitting antennas may be used to transmit signals to a given wireless receiver. When the antennas are individual elements

10   in an antenna array, coherent transmit beamforming may be used to advantage. With this technique, reception performance is improved by the summation of transmit powers received from the multiple transmit antenna elements, as well as by the focusing of the transmit signal towards the receiver.

If the transmit antenna elements are not co-located, spatial transmit diversity may

15   be achieved by transmitting the same signal from multiple, spaced-apart transmit antennas. However, non-coherent (e.g., time-offset) diversity signals transmitted in this manner increase the geographical spread of interference between different wireless receivers using the same communication channel.

With spatial diversity, multiple base stations may be employed to simultaneously

20   transmit to one or more wireless receivers. Individual base stations identify themselves to the respective receivers by transmitting unique pilot codes. In many CDMA systems, the collection of base stations transmit the same pilot code sequence, but each base station uses a different code offset to uniquely identify itself. Under some circumstances, pilot codes from multiple base stations cause interference at the wireless receivers receiving

25   these multiple pilot code signals. Such interference is termed pilot code pollution.

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SUMMARY OF THE INVENTION

The present invention relates to a method of generating and using non-polluting

pilot codes or other dummy signals in a wireless network that employs coherent transmit

5   macro-diversity to permit determination of the requisite downlink channel parameters

where there are fewer receivers than transmitters. Downlink channels are the signal

propagation paths between network transmitters and the various wireless receivers

served by the network. Dummy pilot signals are transmitted to imaginary wireless

receivers in a manner that allows characterization of downlink channels between N

10   transmitters (e.g., antennas) and M receivers, where N > M. The pilot codes are

generated in a manner that does not cause interference in the real receivers. In an

exemplary embodiment, the non-polluting pilot signals are used in a cellular

radiotelephone system that employs coherent transmit macro-diversity.

With coherent transmit macro-diversity, more than one transmit signal is used to

15   carry information for a wireless receiver. When multiple wireless receivers are involved,

each transmit signal comprises a weighted combination of the individual information

signals intended for the different receivers. The weighting is based on the propagation

channels between each receiver and each transmitter, and is designed to cause

reinforcement of the wanted signal with simultaneous cancellation of the unwanted

20   signals at each receiver. That is, the various transmit signals combine at each receiver to

cancel out all but that receiver's wanted signal.

Each receiver provides some form of loop back signal that the network uses to

estimate the downlink channel between that receiver and the various transmitters being

used to transmit to the receiver. A channel estimate matrix may be formed using this

25   information, where each matrix column represents one of the N transmitters, and each

matrix row represents one of the M wireless receivers, thus defining an N x M matrix.

Where N > M, the channel estimate matrix is rank deficient and does not provide enough

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information for the network to determine the downlink channels between each transmitter

and each receiver.

In a simple example where two transmitters transmit to one receiver, the present

invention imagines a second, dummy receiver to exist where the propagation coefficients

5   for the position of the imagined receiver are in some sense orthogonal to those of the real

receiver. A pilot symbol stream is transmitted to the dummy receiver that is statistically

independent and preferably orthogonal. Channel estimates for the downlink channels

between the two transmitters and the one actual receiver are used in pre-filtering the pilot

symbol stream for the dummy receiver. To the extent that the downlink channel

10   estimates are accurate, the pilot symbol stream for the dummy terminal will be non-

polluting with regard to the real receiver. Thus, correlation operations may be performed

using the non-polluting pilot code based on loop back information from the real receiver to

calculate the downlink channels to the real receiver.

In general, where there are N transmitters and M receivers, (N - M) dummy

15   receivers are imagined and dummy pilot code symbol streams are transmitted to each

one. Various techniques are available for figuratively locating the dummy receivers at

positions having downlink path coefficients orthogonal to the paths of the real receivers.

Such techniques may involve arbitrarily rotating multi-dimensional vectors about one or

more similarly dimensioned vectors representing the estimated path coefficients to the

20   real receivers.

In the above operations, adding dummy receivers is equivalent to adding rows to

the channel estimate matrix. It may be seen that by adding each row as the time-reverse

conjugate of its own co-factors, the determinant of the resultant expanded matrix is the

same as the inverse of the original channel estimate matrix multiplied by its time-reverse

25   conjugate. Thus, the above technique preserves the denominator poles of the original

matrix, which means that the desired signal gain achieved from using coherent transmit

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macro-diversity is preserved when using non-polluting pilot codes in accordance with the

present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

5   Fig. 1 is diagram of an exemplary wireless communication network for practicing

coherent transmit macro-diversity.

           Fig. 2 is a diagram of an exemplary transmit processor for implementing transmit

pre-filtering used in macro-diversity transmission.

           Fig. 3 is an exemplary diagram for using non-polluting pilot codes in the network

10   of Fig. 1 to facilitate propagation channel estimation in accordance with the present

invention.

DETAILED DESCRIPTION OF THE INVENTION

           In the Applicant's co-pending application, "COHERENT TRANSMIT MACRO-

15   DIVERSITY IN WIRELESS COMMUNICATION," a novel system and method for

practicing coherent transmit macro-diversity are presented. This co-pending application

is incorporated in its entirety herein by reference. With coherent transmit macro-diversity,

two or more transmitters are used to simultaneously transmit to a wireless receiver. The

transmit signals are weighted based on the downlink propagation channels between each

20   of the transmitters and the receiver. At the receiver, the transmit signals combine in a

manner that reinforces the receiver's desired information signal, while canceling other

information signals intended for other receivers that might also be carried in the transmit

signals. Interference cancellation in this manner relies on forming the transmit signals

based on downlink channel estimates.

25   Fig. 1 is a diagram of an exemplary wireless communication network 10 for

practicing one embodiment of coherent transmit macro-diversity in accordance with the

above-incorporated co-pending application. A plurality of base stations 12 transmit via

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corresponding transmit antennas 14 to a plurality of wireless receivers, shown here as

mobile terminals 16. A central processing system, referred to herein as a transmit

processor 18, provides transmit signals to each base station 12 in baseband form. In

turn, each base station 12 converts its input transmit signal into a form suitable for

5   transmission from its associated antenna 14. The transmit processor 18 may, for

example, be associated with or be part of a mobile switching center (MSC) 19 that

interfaces the network 10 with one or more external networks 21. Such external networks

21 may include the Public Switched Telephone Network (PSTN), and one or more packet

data networks (PDNs), such as the Internet.

10   As illustrated, there is a one-to-one correspondence between the number of

antennas 14 (e.g., transmitting elements or stations) and the number of mobile terminals

16. However, the ratio may be varied such that there are more or fewer transmit stations

than there are wireless receivers. Indeed, the non-polluting pilot codes of the present

invention provide exemplary techniques for practicing coherent transmit macro-diversity

15   where there are fewer receivers than transmitters.

Referring again to the illustration, base station 12A broadcasts transmit signal T_1

via antenna 14A, and likewise, base stations 12B and 12C broadcast transmit signals T_2

and T_3 via antennas 14B and 14C, respectively. Each transmit signal T_X represents a

weighted combination of the different information signals intended for respective ones of

20   the mobile terminals 16. Each mobile terminal 16 receives each of the transmit signals,

albeit through different downlink propagation channels. That is, each mobile terminal 16

receives the combination of T_1, T_2, and T_3, as affected by the propagation channels

between that mobile terminal 16 and point of transmission for T_1, T_2, and T_3.

The set of downlink channels between each transmit antenna 14 and each mobile

25   terminal 16 may be represented using the nomenclature C_{jk}. This symbol denotes the

channel between the jth wireless receiver (e.g., a given one of the mobile terminals 16)

and the kth transmitter (e.g., a given one of the transmit antennas 14). Thus, in the

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illustration, C_{11} denotes the channel between mobile terminal 16A and transmit antenna 14A, C_{12} denotes the channel between mobile terminal 16A and transmit antenna 14B, and so on.

Typically, the propagation channel between a given antenna 14 and a given mobile terminal 16 comprises a number of downlink propagation paths. These multiple propagation paths, referred to as multipaths, each have characteristic attenuation, phase, and delay attributes, which may be expressed as a complex coefficient representing magnitude and phase, and a corresponding delay attribute. Thus, channel coefficient C_{jk} may be represented by the polynomial $C_0 + C_1 z^{-1} + C_2 z^{-2} + ... + C_{n-1} z^{n-1}$, where C_n represents the channel coefficient associated with a single multipath and z^x is a delay operator that represents the unit delay of the various multipaths relative to the first received multipath. The time delay operator could be expressed relative to a multipath other than the first received multipath, in which case the above expression might include channel coefficients with positive delay elements (e.g., $C_x z^{+4}, C_{x-1} z^{+3}$, and so on).

In any case, the above expressions demonstrate that the multipath channel between any transmit antenna 14 and a mobile terminal 16 may be expressed as a polynomial in z, based on the channel coefficients and corresponding path delays associated with the multipaths involved. The complete set of channel coefficients from all antennas to all receivers forms a channel estimate matrix and may be expressed as follows:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \qquad \text{(Eq. 1)}$$

where each matrix element C_{jk} is a polynomial that corresponds to one multipath channel between a given transmit station and a given mobile terminal. Again, transmit station broadly refers to the transmitting element associated with one of the transmit signals.

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In this example, the channel estimate matrix is used to generate transmit signals T_1, T_2, and T_3 in such a manner as to allow the same downlink communication channel to be used by multiple mobile terminals 16 operating within the same service area. The transmit signals T_1, T_2, and T_3 comprise weighted combinations of information signals S_1,

5   S_2, and S_3, which are intended for three different mobile terminals. Information signals S_1, S_2, and S_3 are combined such that at each mobile terminal 16 receives only its wanted signal, with the unwanted signals (e.g., those intended for the other mobile terminals 16) canceling.

To better understand the approach to the unwanted signal cancellation, it is

10   helpful to examine the received signal R at any one of the receivers (e.g., mobile terminals 16). The signal received by a mobile terminal 16 during a given symbol period may be described by the following equation,

$$R(i) = C_0 S(i) + C_1 S(i-1) + C_2 S(i-2) + ... + C_{L-1} S(i-L+1), \qquad \text{(Eq. 2)}$$

where $R(i)$ is the complex value of the received signal sample (with carrier frequency

15   removed) at time instant i, $S(i)$ is the symbol transmitted at time i, C_j is the complex number describing the phase and amplitude of the propagation path with j-symbol periods of delay (relative to the shortest path, C_0), and L represents the number of multipaths between the antenna 14 and the mobile terminal 16.

The combination of a signal with itself delayed in steps of one symbol period may

20   also be described by the use of the Z-transform. A discrete-time signal S that is delayed by one sample is denoted by $z^{-1} \cdot S$, where "z" is the time advance operator and its reciprocal is the time delay operator. Thus the polynomial $a + bz^{-1} + cz^{-2}$ times S means $aS(i) + bS(i-1) + cS(i-2)$.

Therefore, equation (1) can be written as:

25     $$R = C(z^{-1})S \qquad\qquad\qquad \text{(Eq. 3)}$$

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where "C" is now a polynomial, in z^{-1}, with coefficients $C_0 \ldots C_{L-1}$, and R stands for a received signal sample stream, while S stands for the corresponding transmitted symbol stream.

If R_j denotes the signal received at receiver j and T_k denotes the signal transmitted by transmit antenna k, the entire picture of propagation from all antennas 14 to all mobile terminals 16 may be described by the matrix equation,

$$[R] = [C] \cdot [T] \tag{Eq. 4}$$

where C is the channel estimate matrix from Eq. 1. For the 3 x 3 example of Fig. 1, Eq. (4) is expressed as,

$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} * \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \tag{Eq. 5}$$

Here, R_1 is the composite signal received at mobile terminal 16A, R_2 is the composite signal received at mobile terminal 16B, and R_3 is the composite signal received at mobile terminal 16C. Similarly, T_1 is the transmit signal from antenna 14A, T_2 is the transmit signal from antenna 14B, and T_3 is the transmit signal from antenna 14C. Thus, each R_x is a composite of the three transmit signals T_1, T_2, and T_3 , each one received through a different propagation path relative to the receiver receiving R_x. In turn, each of the transmit signals T_k comprises differently weighted components of each of the desired information signals S_1, S_2, and S_3.

If we desire each receiver j (e.g., a given mobile terminal 16) to receive only its intended symbol stream S_j, then the transmit signals T_k needed to achieve that are given by,

$$[T] = [C]^{-1} \cdot [S] \tag{Eq. 6}$$

where $[C]^{-1}$ is the inverse of the channel estimate matrix $[C]$, and $[S]$ is the matrix of desired information symbol streams intended for the set of mobile terminals 16. In Eq.

(6), each T_k in [T] comprises a weighted combination of the information symbol streams S_j intended for each receiver. Assuming that the channel coefficients for the propagation paths are estimated correctly, multiplication of the symbol stream matrix [S] by the inverse of the channel estimate matrix $[C]^{-1}$ yields the transmit symbol matrix [T] which results in

5   complete cancellation of the unwanted signals at each mobile terminal 16. Thus the problem at hand concerns how to invert the channel estimate matrix [C] of z-polynomials, and whether such an entity exists and is numerically well or ill conditioned.

Matrix theory describes the procedure for computing the inverse of a matrix as follows. First, transpose the matrix then replace every element by its cofactor to obtain a

10   matrix known as the adjoint matrix. Then divide each element of the adjoint matrix by the determinant of the original matrix to obtain the inverse matrix.

The determinant of a matrix is given by sums of products of its elements and is computable in a deterministic fashion. For example, assuming the following 3 x 3 channel estimate matrix,

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$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$
(Eq. 7)

the determinant may be calculated as:

$$C_{11}(C_{22} \cdot C_{33} - C_{32} \cdot C_{23}) - C_{12}(C_{21} \cdot C_{33} - C_{31} \cdot C_{23})$$
$$+ C_{13}(C_{21} \cdot C_{32} - C_{31} \cdot C_{22})$$
(Eq. 8)

The cofactor of element C_{11} is $(C_{22} \cdot C_{33} - C_{32} \cdot C_{23})$, which is therefore the first element of the adjoint matrix. The first element of the inverse matrix is thus,

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$$\frac{(C_{22} \cdot C_{33} - C_{32} \cdot C_{23})}{C_{11}(C_{22} \cdot C_{33} - C_{32} \cdot C_{23}) - C_{12}(C_{21} \cdot C_{33} - C_{31} \cdot C_{23}) + C_{13}(C_{21} \cdot C_{32} - C_{31} \cdot C_{22})}$$
(Eq. 9)

When each matrix element C_{jk} in the above expression is a z-polynomial, it may be deduced that the expression's numerator is a z-polynomial of twice the order of the C_{jk},

while the denominator is a polynomial of three times the order of C_{jk}. Therefore, the

inverse matrix comprises elements that have both a numerator z-polynomial and a

denominator z-polynomial. According to Eq. 6, information bearing signals S_j to be

transmitted to the mobile terminals 16 must be processed by multiplication with respective

5   inverse matrix elements and summed to produce the transmit signals T_k.

If the exact inverse C-matrix (downlink channel coefficient matrix) is applied to the

information signals S_j to form the transmit signals T_k from each of the antennas 14, the

mobile terminals 16 will receive only their intended information signal S_j with multipath

interference already cancelled at the transmitter, since the resulting channel from the

10   transmitter to the receiver is $[C] \cdot [C]^{-1}$, which is unity.

Referring still to Fig. 1, information symbol streams S_1, S_2, and S_3 intended

respectively for mobile terminals 16A, 16B, and 16C are input to a central transmit

processor 18 that serves a plurality of base stations 12A, 12B and 12C. Transmit

processor 18 includes a numerical processor 20 to perform the matrix operations on the

15   information signals as described above. Using knowledge of the multipath channels C_{jk},

the numerical processor 20 filters the information signals S_1, S_2 and S_3 and forms

weighted combinations of the information signals S_1, S_2 and S_3 to generate transmit

signals T_k. The information signals S_1 S_2 and S_3 may be processed by the numerical

processor 20 at baseband, which equates to symbol-rate processing. Processing by the

20   numerical processor 20 is described in greater detail below.

The transmit signals T_k are relayed from the transmit processor 18 to respective

base stations 12A, 12B, and 12C, where they are converted to continuous time

waveforms by digital-to-analog converters (not shown) and up-converted to a desired

radio frequency channel by modulators 22 in respective base stations 12A, 12B, and 12C.

25   The up-converted signals are then amplified to desired transmit power levels by PAs 26 in

each of the base stations 12 and transmitted by respective antennas 14A, 14B, and 14C.

Jointly transmitting the desired information signals as combined transmit signals from the respective transmitters may be synchronized, for example, by the MSC 19, which could provide a synchronization signal to each of the transmitting base stations 12.

The transmit signals T_k (e.g., T_1, T_2, and T_3) propagate to the mobile terminals
5 16A, 16B, and 16C by way of the multipath channels C_{jk}. With the generation of the transmit signals T_k, each mobile terminal 16 receives only the information signal intended for that mobile terminal 16 with the unwanted information signals canceling.

Figure 2 illustrates the transmit processor 18 and numerical processor 20 in greater detail. The illustration assumes N transmit antennas 14 transmitting N transmit
10 signals to $N = M$ mobile terminals 16. Numerical processor 20, as previously described, processes the information signals S_1, S_2 and S_3 to form the set of transmit signals , T_1 T_2 and T_3 that results in unwanted signal cancellation at each mobile terminal 16. Numerical processor 20 comprises a set of IIR filters 30 and an array 32 of FIR filters 34. Transmit processor 18 includes, in addition to the numerical processor 20, a channel estimator 36
15 and a matrix calculator 38.

The channel estimator 36 derives the set of channel coefficients characterizing the multipath channels C_{jk} between each of the antennas 14 and each of the mobile terminals 16. The set of coefficients output from channel estimator 36 is referred to herein as channel state information (CSI). The channel estimator 36 outputs these
20 channel coefficients to the matrix calculator 38, which calculates the coefficients of the IIR and FIR filters as previously described. More particularly, the channel estimator 36 provides N x N x L channel coefficients describing the N x N multipath channels C_{jk} from each one of the N antennas 14 to each one of the N mobile terminals 16. L is the impulse response length of the multipath channels C_{jk}, which equates to the number of multipaths
25 in each multipath channel C_{jk} .

Treating each set of channel coefficients as a z-polynomial of order L and as an element of an N x N square matrix (i.e., the channel estimate matrix above), the matrix

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calculator 38 forms the N x N adjoint matrix, whose elements are polynomials of order (N

- 1)L, and a determinant polynomial of order NL.   Matrix calculator 38 factors the

determinant polynomial to determine the NL roots of the determinant polynomial and

deletes the L roots having smallest absolute value of logmagnitude, leaving (N-1)L roots

5   forming a reduced determinant polynomial of order (N-1)L.   The reduced determinant

polynomial determines the IIR filter as previously described and the adjoint matrix

determines the coefficients of the FIR filters 34 in filter array 32.

The information bearing signals S_j (e.g., symbol streams S_1 , S_2, and S_3) carrying

desired information for mobile terminals 16A, 16B, and 16C, respectively are input to

10   numerical processor 20. Within the numerical processor 20, signals S_j are processed

through IIR filters 30 of order (N-1)L corresponding to the reduced denominator

polynomial and through FIR filters 34 of order (N-1)L corresponding to the adjoint matrix

polynomials as follows.

Information blocks intended to be transmitted to different mobile terminals 16 are

15   assembled in the transmit processor 18. First the information signals are IIR filtered by

the respective IIR filters 30A-30N, which compensates for anticipated intersymbol

interference (ISI) caused by delayed versions of the same signal S_j. In this exemplary

implementation, the IIR filters 30 are formed from the determinant z-polynomial of the

channel estimate matrix [C], and may be reduced in order by omission of factors

20   corresponding to roots closest to the unit circle as previously described. The number of

roots omitted may be anything from none up to the equalizer capability of the respective

mobile terminals 16. The IIR filters 30 comprise one or more filter elements

corresponding to the reciprocals of the roots of the reduced determinant z-polynomial.

Each information block is passed in the reverse time direction through those filter

25   elements formed from the reciprocals of roots of the reduced determinant that have a

magnitude greater than unity and in the forward time direction through filter elements

formed from the reduced determinant roots of magnitude less than unity to obtain

IIR-processed blocks.

The IIR processed blocks are then FIR processed by matrix multiplication with the

adjoint matrix polynomials to obtain transmit signal blocks.   Filter array 32 comprising

5   FIR filters 34 process the IIR-filtered signals to compensate for interference between

signals S_1, S_2 , and S_3 at the mobile terminals 16. Each signal is processed by a

corresponding row of FIR filters 34 in the FIR filter array 32. The output signals from FIR

filters 34 are summed down filter array columns, indicated by the + sign at the junction of

the line from one output to another. These summed outputs represent the baseband

10   combined transmit signals relayed by the transmit processor 18 to the modulators 22

used to generate transmit signals T_1 ... T_N, which are in turn transmitted by transmit

antennas 14A ... 14N.

Note that each of the FIR filters 34 is updated with new coefficients as needed

based on changing propagation path channel coefficients. Also, note that the FIR filters

15   34 in the filter array 32 correspond to elements in the adjoint of the channel estimate

matrix C. Thus, each signal input into the filter array 32 is processed by a row of filters 34

corresponding to a respective row in the adjoint matrix discussed above.

The transmit signal may be further filtered to restrict transmission bandwidth and

up-sampled and converted to continuous time signals. The transmit signals, denoted as

20   T_1, T_2, and T_3 in the illustration, are output by the transmit processor 18 and coupled to

corresponding base stations 12, which may be base transceiver stations (BTSs). A

modulator 22 in each BTS modulates the input transmit signal onto an RF carrier signal,

which is amplified by a suitable RF power amplifier (PA) 26 to make the transmit signals

(i.e., T_1, T_2, or T_3) discussed above suitable for transmission. Since IIR, FIR and

25   bandwidth-restriction filtering are all linear processes, they may be carried out in any

order. Generating T_1, T_2, and T_3 in this manner causes the combination of transmit

signals to cancel differently at each mobile terminal 16, such that each mobile terminal 16 receives only its desired signal.

Earlier reference was made to practicing coherent transmit macro-diversity with varying ratios of transmitters and receivers. Fig. 3 illustrates the network 10 with

5   additional details where there are two transmitters and one wireless receiver. Later discussion expands this to the more generalized case of N transmitters and M receivers, where N > M. A network receiving system 50 and a loop back signal processor 52 allow the network 10 to determine how much interference is caused at one or more receivers by one or more transmitted dummy signals for reasons explained later.

10   In Fig. 3, the information signal $X(z)$ for the mobile terminal 16 feeds into the transmit processor 18. The information signal $X(z)$ may be, for example, a chip, symbol, or signal sample stream. In this example, the transmit processor 18 operates on the single information signal $X(z)$ to produce Right-Hand Circular (RHC) and Left-Hand Circular (LHC) polarized transmit signals by passing $X(z)$ through transmit pre-filters $P_1(z)$

15   and $P_2(z)$, respectively. Thus, in this exemplary implementation, two separate transmitters are formed by using two cross-polarized antennas on the same mast or tower. However, other implementations can be used in which the separate transmitters are located at different sites and may have the same or different polarizations. Transmit pre-filters $P_1(z)$ and $P_2(z)$ are determined within the network 10 and, hence, are known to

20   the transmit processor 18.

The resultant two transmit signals $P_1(z)X(z)$ and $P_2(z)X(z)$ are passed to the base station 12, where they are translated into a format suitable for transmission from the dual polarized antenna 14. That is, the two transmit signals are each transmitted to the mobile terminal 16 on different polarizations. The mobile terminal 16 receives the signals after

25   propagation through the different propagation channels for the two signal polarizations, where the RHC channel is expressed as $CR'(z)$ and the LHC channel as $CL'(z)$. The mobile terminal thus receives $Y(z) = (P_1(z)CR'(z)+P_2(z)CL'(z))X(z)$.

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The mobile terminal 16 provides a network receiving system 50 with a composite loop back signal. Note that the receiving system 50 is diagrammed separately here for clarity of discussion, but in actual application may simply be incorporated into the base station 12 as part of its normal radio transceiver interface. Loop back processing entails

5   correlating the loop back signal from the mobile terminal 16 in the loop back processor 52 and correcting for uplink channel effects, after which the Y(z) signal is recovered and the composite downlink channel $P_1(z)CR'(z) + P_2(z)CL'(z)$ is obtained.

However, this cannot be uniquely portioned to determine estimated downlink channels CR(z) and CL(z) corresponding to the actual channels CR'(z) and CL'(z) given

10   $P_1(z)$ and $P_2(z)$, as witnessed by the fact that the above expression is identical to $P_1(z)(CR'(z) + aP_2(z)) + P_2(z)(CL'(z) - aP_1(z))$. Thus, because the terms $P_1(z)aP_2(z)$ and $-P_2(z)aP_1(z)$ cancel, it is not possible to determine an estimate for CR'(z) within an arbitrary multiple "a" of $P_2(z)$ nor is it possible to determine an estimate of CL'(z) within an arbitrary multiple "a" of $P_1(z)$.

15   The present invention determines one or more other information signals, streams, or pilot codes for joint transmission with the information signal transmissions to the real receivers that enables determination of the downlink channels between the transmitters and the real receivers. In the current example, transmitting a dummy pilot code as an additional pilot code signal permits estimation of CR'(z) and CL'(z) without causing added

20   interference at the mobile terminal 16. In general, one or more dummy signals are transmitted along with the information signals. The dummy signals are pre-filtered along with the information signals in the transmit processor 18 in a manner that will result in cancellation of the dummy signals at each mobile terminal 16, provided that the propagation channel estimates used by the transmit processor 18 in transmit pre-filtering

25   substantially match the actual propagation channels between the transmitters and the receivers. In this way, the extent to which the dummy signal does interfere at the

receivers may be used to guide adjustment of the propagation channel estimates so that they more closely match the actual channel characteristics.

In the context of the current dual-polarization, single mobile terminal example, a dummy pilot code $S(z)$ is transmitted on each antenna polarization. Pre-filtering is
5   applied to the signal $S(z)$, such that $-CL(z)S(z)$ is transmitted from the RHC antenna element of antenna 14, while $CR(z)S(z)$ is transmitted by the LHC antenna element. Here, the $CL(z)$ and $CR(z)$ terms are estimates of the actual downlink channels $CL'(z)$ and $CR'(z)$, rather than the actual downlink channels.

Thus, the mobile terminal 16 receives $(-CL(z)CR'(z) + CR(z)CL'(z))S(z)$, which
10   equals zero (0) if the channel estimates match the actual downlink channels. That is, the dummy pilot signal cancels out at the mobile terminal 16 if the pre-filtering polynomial $CL(z)$ matches $CL'(z)$ and pre-filtering polynomial $CR(z)$ matches $CR'(z)$. The dummy pilot code $S(z)$ would be received strongest at a virtual receiver location to which the propagation channels were $-CL(z)^{\#}$ for the RHC and $CR(z)^{\#}$ for the LHC. Here the "#"
15   symbol denotes the time-reverse, conjugate transpose of a matrix. Detailed descriptions of this notation and the underlying operations appear in the previously incorporated, co-pending application entitled "COHERENT TRANSMIT MACRO-DIVERSITY."

The channel estimate matrix for the intended signal to the mobile terminal 16 and the dummy pilot signal is thus given as,

20
$$[C] = \begin{bmatrix} CR & CL \\ -CL^{\#} & CR^{\#} \end{bmatrix}$$

which is now square. The pre-filter for transmitting $X(z)$ to the real mobile terminal 16 and $S(z)$ so as not to interfere with the mobile terminal 16 is the adjoint of the above matrix, and is thus expressed as,

$$\begin{bmatrix} CR^{\#} & CL^{\#} \\ -CL & CR \end{bmatrix},$$

25   which may be expressed in terms of the transmit filters $P_1(z)$ and $P_2(z)$ as,

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$$\begin{bmatrix} P_1(z) & P_2(z) \\ -P_2(z)^{\#} & P_1(z)^{\#} \end{bmatrix}.$$

With the above pre-filter, the loop back signal received from the real mobile terminal is,

$$(P_1(z)CR'(z) + P_2(z)CL'(z))X(z) + (P_1^{\#}(z)CL'(z) - P_2^{\#}(z)CR'(z))S(z).$$

Correlation with the independent symbol streams $X(z)$ and $S(z)$ after compensation of the

5   loop back signal for the uplink channel effects yields,

$$P_1(z)CR'(z) + P_2(z)CL'(z) \text{ for correlation with } X(z), \text{ and}$$

$$-P_2^{\#}(z)CR'(z) + P_1^{\#}(z)CL'(z) \text{ for correlation with } S(z).$$

These two expressions are sufficient for calculating estimates of the actual downlink

channels $CR'(z)$ and $CL'(z)$ to be used in transmit pre-filtering.

10   Imagining a virtual or dummy terminal to exist where its propagation channels

were in some sense orthogonal to those of the real mobile terminal 16 solved the

information deficiency in the above example where the channel estimate matrix was 1

row x 2 columns (i.e., one real information signal and receiver and two transmitters).

Adding the dummy pilot signal $S(z)$ made this matrix square (2 x 2). The matrix elements

15   in the additional row arising from $S(z)$ being transmitted to the virtual location of the

dummy terminal may be seen to be the time-reverse conjugates of the elements'

cofactors. The determinant of the 2 x 2 channel estimate matrix is thus of the form,

$$CR(z)CR^{\#}(z) + CL(z)CL^{\#}(z),$$

which is the same as $[C \ C^{\#}]$, where "C" represents the original 1 x 2 matrix before

20   supplementing with a row vector for $S(z)$ as above, and $C^{\#}$ is the time-reverse conjugate

transpose of C. The addition of the row vector for the dummy terminal and its

propagation channels has therefore not affected the poles of the denominator of the over-

dimensioned problem (i.e., the deficient 1 x 2 channel estimate matrix). The desirable

gain of the over-dimensioned solution therefore remains intact.

25   A solution for a three-transmitter/two-receiver scenario may be deduced as

follows:

Let the starting, information deficient 2 x 3 channel estimate matrix be expressed as,

$$C = \begin{bmatrix} C_{11}(z) & C_{12}(z) & C_{13}(z) \\ C_{21}(z) & C_{22}(z) & C_{23}(z) \end{bmatrix},$$

where the rows correspond to the two real receivers (e.g., mobile terminals 16) and the columns correspond to the three transmitters (e.g., three base stations 12).

5   The imagined third receiver needed to make the above channel estimate matrix square should have dummy propagation channels forming a third row vector of polynomials that is orthogonal to both of the first two rows. A three-element vector "V" perpendicular to the two given three-element vectors represented by rows 1 and 2 can be formed from the cross product of row 1 and row 2 as,

10        $V = $ row 1 X row 2 $= C_{12}C_{23} - C_{22}C_{13};\ C_{13}C_{21} - C_{11}C_{23};$ and

$C_{11}C_{22} - C_{12}C_{21}.$

The virtual channel, that is the channel(s) to the imagined or dummy terminal, should be chosen to be the time-reverse conjugate of the above. Namely, row 3 should be chosen as $V^{\#}$, such that,

15        $C_{31} = C_{12}{}^{\#}C_{23}{}^{\#} - C_{22}{}^{\#}C_{13}{}^{\#},$

$C_{32} = C_{13}{}^{\#}C_{21}{}^{\#} - C_{11}{}^{\#}C^{23\#},$ and

$C_{33} = C_{11}{}^{\#}C_{22}{}^{\#} - C_{12}{}^{\#}C_{21}{}^{\#},$.

where each element of the third row may be verified to be the time-reverse conjugate of the element's cofactor. Thus, in the expansion of the 1 x 2 case and in the expansion of

20   the 2 x 3 case to completely determined 2 x 2 and 3 x 3 cases, respectively, using virtual channel construction as above, there is no alteration of determinant poles. Thus, virtual channel construction in accord with the present invention preserves the efficiency and advantages of the over-dimensioned N transmitters x M receivers condition, where N > M.

Where three transmitters, such as three base stations 12, collaborate to form a

25   coherent macro-diversity transmission to a single mobile terminal 16, two non-polluting pilot-code transmissions (e.g., S1(z) and S2(z)) are added. The virtual location of the two

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dummy terminals are selected based on orthogonality considerations with respect to propagation channel(s) of the real terminal 16.

When two vectors are given in three-dimensional space, a third vector perpendicular to both of them is unique; however, when only one vector in three-
5   dimensional space is given, constructing another two perpendicular vectors is not represented by a unique solution. Instead, such vector construction involves the arbitrary rotation about the given vector.

For example, given channels C_{11}, C_{12}, and C_{13} in the first row, a dummy vector may be constructed for the second row as 0, $-C_{13}^{\#}$, and $C_{12}^{\#}$, and used for transmitting a
10   first dummy pilot signal $S_1(z)$. Then, the elements in the third row vector for transmitting the second dummy pilot signal $S_2(z)$ may be determined to be equal to the time-reverse conjugate of the elements' cofactors. This may be expressed as,

$$C_{31} = C_{12}C_{12}^{\#} + C_{13}C_{13}^{\#},$$

$$C_{32} = -C_{11}^{\#}C_{12}, \text{ and}$$

15   $$C_{33} = -C_{11}^{\#}C_{13}.$$

However, other choices may be found for row 2, which would result in other values being calculated for row 3. In all cases, however, the vectors for the added rows are chosen to preserve the denominator poles and thus the efficiency of the over-dimensioned 1 x 3 condition.

20   Generally, a mobile terminal 16 may be located within a triangle of three base stations 12, and therefore the above discussion of polynomial matrices was limited to a maximum dimension of three. However, it may be deduced by extrapolation that the elements in a virtual Nth row in an N -1 x N over-dimensioned channel estimate matrix would turn out to be the time-reversed conjugate of those elements' cofactors in the
25   squared up N x N channel estimate matrix. Likewise, in an N - 2 x N problem, the N - 1 row may be determined by setting any polynomial element in the N - 2 row to zero and making the remaining N - 1 polynomials in that row the time-reverse conjugates of their

own cofactors in the N - 1 x N - 1 matrix formed from the remaining rows and columns not containing the zero polynomial. Then, the Nth row may be filled in as above.

As an example, assume that four base stations 12 will transmit information signals to two mobile terminals 16. The channel estimate matrix initially comprises a 2 x 4 matrix

5   expressed as,

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \end{bmatrix},$$

where row 1 corresponds to the information signal for receiver 1 (i.e., one of the two mobile terminals 16), row 2 corresponds to receiver 2 (i.e., the other mobile terminal 16), and columns 1 through 4 correspond to transmitters 1 - 4 (i.e., the four base stations 12).

10   Here, the starting matrix C will be supplemented with two additional rows corresponding to dummy pilot signals in order to make the channel estimate matrix square. First, a 3 x 4 matrix is formed by adding the first supplemental row to the starting matrix as its third row. The supplemental row may be considered to be a channel estimate vector for the propagation channels between the four transmitters and the

15   imagined location of the virtual receiver to which the first dummy pilot signal will be transmitted.

To determine the values of each element in this third row, one row element is made zero, and the column in which that element is located is not considered in cofactor calculations for the remaining elements in the third row. The cofactor of each remaining

20   element in the third row of the 3 x 4 matrix is then calculated using the various 2 x 2 cofactor matrices formed using the values in the two starting rows, with the final value of each third row element being set as the time-reverse conjugate of its cofactor. Thus, the 3 x 4 channel matrix now appears as,

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ 0 & \alpha^{\#}_{32} & \alpha^{\#}_{33} & \alpha^{\#}_{34} \end{bmatrix},$$

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where "α_{ij}" denotes the cofactor of matrix element in row i, column j, and "#" denotes the time-reverse conjugate operator as defined earlier. Of course, any of the row 3 elements could have been arbitrarily made zero in the above example, and the cofactor calculations varied accordingly.

5   Now, with the N -1 row added (i.e., the third row), the Nth or fourth row is added. The elements of the fourth row are calculated as the time-reverse conjugates of each row element's cofactor. Thus, the channel estimate matrix used to pre-filter the jointly transmitted information signals and dummy pilot signals is given as,

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ 0 & \alpha_{32}^{\#} & \alpha_{33}^{\#} & \alpha_{34}^{\#} \\ \alpha_{41}^{\#} & \alpha_{42}^{\#} & \alpha_{43}^{\#} & \alpha_{44}^{\#} \end{bmatrix}.$$

10   The above channel estimate matrix thus represents the original or starting 2 x 4 matrix supplemented with two additional rows (i.e., rows 3 and 4) corresponding to two dummy pilot signals. Because the matrix elements in rows 3 and 4 are computed or manipulated such that they are in some sense orthogonal to rows 1 and 2, the two dummy pilot signals should not cause interference at the mobile terminals 16.

15   However, to the extent that the estimated channel coefficients in the starting rows do not match the actual propagation channel characteristics to the real mobile terminals 16, the supplemental row values will not cause the desired cancellation of the dummy pilot signals at the mobile terminals 16. Thus, the extent to which the dummy pilot signals interfere with reception at the real receivers may be taken as an indicator of how well the

20   channel estimates for the real receivers match actual channel conditions.

On this basis, the mobile terminals 16 may provide an indication of such interference by providing the loop back signals discussed above to the network 10. Correlation operations between the loop back signals and the pilot and information signals allows the network 10 to determine the extent of pilot signal interference, and thus

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change or update the channel estimates for the real receivers to reduce such

interference.

Thus, dummy signals transmitted in accordance with the above discussion permit

determination of the downlink channel estimates for the propagation paths between the

5   involved transmitters and the wireless receivers being served by those transmitters. The

· signals being transmitted to a reduced number of mobile terminals 16 (i.e., N transmitters

transmitting to M receivers where N > M) may be pre-filtered for transmission such that

the dummy signals allowing channel estimation cause no interference or pilot pollution at

the real mobile terminals 16.·

10   Note that the transmit processor 18, the loop back processor 52, and various

other portions of the network 10 are subject to much variation in terms of implementation.

Generally, the transmit processor 18 and loop back processor 52 comprise one or more

signal processors, or comprise portions of other network processing systems within the

network 10. For example, if the MSC 19 contains the transmit processor 18, it may be

15   that the transmit processor 18 comprises processing resources within the MSC 19. It

may be that the loop back processor 52 is formed as part of the transmit processor 18,

such that a central processing system of the network 10 determines transmit pre-filtering

based on receiving and processing loop back signal information.

Of course, the present invention is in general subject to much variation, and the

20   above examples should be considered as exemplary rather than limiting. Indeed, the

present invention is limited only by the following claims and the reasonable equivalents

thereof.

CLAIMS

What is claimed is:

1.   A method of estimating propagation channels between two or more transmitters

and a fewer number of receivers, the method comprising:

5   transmitting information signals for said receivers jointly from said two or more

                transmitters, said information signals pre-filtered based on propagation

                channel estimates;

        transmitting at least one dummy pilot signal jointly from said transmitters, said at

                least one dummy pilot signal pre-filtered based on said propagation

10   channel estimates; and

        receiving loop back signals from said receivers having dummy pilot signal

                interference that is dependent on the accuracy of said propagation channel

                estimates; and

        revising said propagation channel estimates based on said loop back signals.

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2.   The method of claim 1 wherein revising said propagation channel estimates based

on said loop back signals comprises:

        correlating said loop back signals with said information signals to determine an

                amount of dummy pilot signal interference; and

20   adjusting said propagation channel estimates to reduce said dummy pilot signal

                interference in said loop back signals.

3.   The method of claim 1 wherein said propagation channel estimates comprise

propagation channel estimate vectors relating each said receiver to said transmitters, and

25   further comprising determining a supplemental channel estimate vector for each one of

said at least one dummy pilot signal, such that said supplemental channel estimate

vectors are orthogonal to said channel estimate vectors.

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4.   The method of claim 3 wherein pre-filtering said at least one dummy pilot signal based on said propagation channel estimates comprises pre-filtering said at least one dummy pilot signal using said supplemental channel estimate vector.

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5.   The method of claim 1 wherein transmitting information signals for said receivers jointly from said transmitters comprises transmitting an information signal for one receiver jointly from two transmitters.

10   6.   The method of claim 5 wherein transmitting an information signal for one receiver jointly from two transmitters comprises transmitting the information signal on two transmit polarizations, wherein each said polarization propagates through a different propagation channel to said receiver.

15   7.   The method of claim 1 wherein transmitting information signals for said receivers jointly from said transmitters comprises transmitting a combination of information signals for a first plurality of receivers from each one in a larger plurality of transmitters.

8.   The method of claim 7 wherein said transmitters are radio base stations, and

20   wherein comprises pre-filtering said information signals to form a combined transmit signal for each one of said transmitters, said combined transmit signals representing differently weighted combinations of said information signals based on said pre-filtering using said propagation channel estimates.

25   9.   The method of claim 8 further comprising pre-filtering said at least one dummy pilot signal, such that said combined transmit signals further comprise a weighted version of said at least one dummy pilot signal.

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10.   A method of facilitating estimation of propagation channels between a first number
of transmitters and a lesser number of receivers, the method comprising:

transmitting information signals for said receivers jointly from said transmitters

based on propagation channel estimates, such that interference between

5   information signals is reduced at each said receiver; and

transmitting a number of dummy pilot signals equal to a difference between the

number of transmitters and receivers, such that said dummy pilot signals

cause substantially no interference in reception of said information signals

by said receivers when said propagation channel estimates substantially

10   match said propagation channels.

11.   The method of claim 10 further comprising, for each said dummy pilot signal
transmitted, calculating propagation channel estimates for a virtual receiver location
corresponding to said dummy pilot signal.

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12.   The method of claim 10 further comprising choosing said virtual receiver location
to be a location relative to said transmitters such that reception of said dummy pilot signal
jointly transmitted by said transmitters would be strongest.

20   13.   The method of claim 12 wherein propagation channel estimates for each said
receiver relative to said transmitters comprise a channel estimate vector, and wherein
choosing a virtual receiver location comprises determining a supplemental channel
estimate vector orthogonal to said channel estimate vectors of said receivers.

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14.   The method of claim 10 further comprising forming said propagation channel

estimates into a channel estimate matrix comprising a matrix column for each said

transmitter and a matrix row for each said receiver, such that a matrix element represents

5   propagation channel estimates between a given transmitter and a given receiver, and

wherein each said matrix row comprises a channel estimate vector.

15.   The method of claim 14 further comprising making said channel estimate matrix

square for use in pre-filtering said information signals and said dummy pilot signals before

10   transmission by supplementing said channel estimate matrix based on adding

supplemental channel estimate vectors as additional matrix rows, wherein each

supplemental channel estimate vector corresponds to one of said dummy pilot signals

being transmitted by said transmitters.

15   16.   The method of claim 15 further comprising computing said supplemental matrix

rows to be orthogonal to said channel estimate vectors for said receivers.

17.   The method of claim 15 wherein transmitting information signals for said receivers

jointly from said transmitters based on propagation channel estimates comprises pre-

20   filtering said information signals based on said channel estimate matrix such that each

transmitter transmits a weighted combination of said information signals, and wherein

said weighted combinations of said information signals combine at each said receiver to

substantially cancel the information signals for the other receivers.

18.   The method of claim 17 wherein transmitting a number of dummy pilot signals

equal to a difference between the number of transmitters and receivers comprises pre-

filtering said dummy pilot signals based on said channel estimate matrix, such that said

5   dummy pilot signals substantially cancel at each said receiver, and wherein an amount of

interference caused by said dummy pilot signals at each said receiver is a function of

mismatch between said propagation channel estimates for that receiver and the actual

propagation channels to that receiver.

10   19.   The method of claim 18 further comprising:

        determining dummy pilot signal interference at said receivers; and

        adjusting said propagation channel estimates based on said determined dummy

                pilot signal interference.

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